Biases in Multi-GNSS Processing

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NGK Summer School
Overview

Observation Equation

GNSS Code Biases

GNSS Phase Biases

Inter-System Antenna Bias
Observation Equation

\[
P^k_i = \left| (\vec{x}^k_i + \Delta \vec{x}^k_i) - (\vec{x}^i_i + \Delta \vec{x}^i_i) \right| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L^k_i = \left| (\vec{x}^k_i + \Delta \vec{{\chi}}^k_i) - (\vec{x}^i_i + \Delta \vec{{\chi}}^i_i) \right| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
\]

\[+ \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i\]
Observation Equation

\[ \begin{align*}
P^k_i &= \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \\
L^k_i &= \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \\
&\quad + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i
\end{align*} \]

position vector of satellite \( k \) related to its center of mass
Observation Equation

\[ P_{ik} = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_{ik}^k + I_{ik}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ik} = |(\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_{ik}^k - I_{ik}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

+ \lambda^k \cdot \Delta \varphi_i^k

- \vec{x}^k

position vector of satellite \( k \) related to its center of mass

\( \Delta \vec{x}^k, \Delta \vec{\chi}^k \)

vector from the center of mass of the satellite \( k \) to the antenna signal emission point for code and phase observations
Observation Equation

\[ P_i^k = |(\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - \alpha^k) \]

\[ L_i^k = |(\vec{x}_k^k + \Delta \vec{\chi}_k^k) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

- **\( \vec{x}_k^k \)**: position vector of satellite \( k \) related to its center of mass
- **\( \Delta \vec{x}_k^k, \Delta \vec{\chi}_k^k \)**: vector from the center of mass of the satellite \( k \) to the antenna signal emission point for code and phase observations
- **\( \delta^k \)**: clock correction of the satellite \( k \) with respect to GPS time
Observation Equation

\[
P_i^k = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - \alpha^k)
\]

\[
L_i^k = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k
\]

- \( \vec{x}^k \): position vector of satellite \( k \) related to its center of mass
- \( \Delta \vec{x}^k, \Delta \vec{\chi}^k \): vector from the center of mass of the satellite \( k \) to the antenna signal emission point for code and phase observations
- \( \delta^k \): clock correction of the satellite \( k \) with respect to GPS time
- \( \alpha^k, \alpha_i^k \): hardware delay in the satellite \( k \) for code and phase measurements
Observation Equation

\[ P^k_i = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T^k_i + I^k_i + c \cdot (\delta - a_i) - c \cdot (\delta^k - a^k) \]

\[ L^k_i = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T^k_i - I^k_i + c \cdot (\delta - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i \]
Observation Equation

\[
P^k_i = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L^k_i = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \phi^k_i
\]

\[I^k_i \quad \text{signal delay in the ionosphere}\]
\[ P_k^i = |(\vec{x}_k^i + \Delta \vec{x}_k^i) - (\vec{x}_i^i + \Delta \vec{x}_i^i)| + T_k^i + I_k^i + c \cdot (\delta_i - a_i) - c \cdot (\delta_k - a_k) \]

\[ L_k^i = |(\vec{x}_k^i + \Delta \vec{x}_k^i) - (\vec{x}_i^i + \Delta \vec{x}_i^i)| + T_k^i - I_k^i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta_k - \alpha_k) \]

+ \lambda_k \cdot N_k^i + \lambda_k \cdot \Delta \varphi_k^i

\[ I_k^i \] signal delay in the ionosphere

\[ T_k^i \] signal delay in the troposphere
\[ P_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta_i^k - a_i^k) \]

\[ L_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta_i^k - \alpha_i^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]
**Observation Equation**

\[
P_i^k = \left| (\vec{x_i^k} + \Delta \vec{x_i^k}) - (\vec{x_i} + \Delta \vec{x_i}) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L_i^k = \left| (\vec{\chi_i^k} + \Delta \vec{\chi_i^k}) - (\vec{\chi_i} + \Delta \vec{\chi_i}) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k
\]

- \(\delta_i\): clock correction of the receiver at the station \(i\) with respect to GPS time
Observation Equation

\[
P_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
\]

\[
+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k
\]

\(\delta_i\) clock correction of the receiver at the station \(i\) with respect to GPS time

\(a_i, \alpha_i\) hardware delay in the receiver at the station \(i\) for code and phase measurements
Observation Equation

\[ P_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = \left| (\vec{x}_i^k + \Delta \vec{\chi}_i^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda_k \cdot N_i^k + \lambda_k \cdot \Delta \varphi_i^k \]

- \( \delta_i \) clock correction of the receiver at the station i with respect to GPS time
- \( a_i, \alpha_i \) hardware delay in the receiver at the station i for code and phase measurements
- \( \Delta \vec{x}_i, \Delta \vec{\chi}_i \) vector from the marker of the station i to the antenna signal reception point for code and phase observations
\[ P^k_i = |(\vec{x}^k_i + \Delta \vec{x}^k_i) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L^k_i = |(\vec{x}^k_i + \Delta \vec{x}^k_i) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \phi^k_i \]

- \( \delta_i \) clock correction of the receiver at the station \( i \) with respect to GPS time
- \( a_i, \alpha_i \) hardware delay in the receiver at the station \( i \) for code and phase measurements
- \( \Delta \vec{x}_i, \Delta \vec{x}_i \) vector from the marker of the station \( i \) to the antenna signal reception point for code and phase observations
- \( \vec{x}_i \) position vector of marker at station \( i \)
Observation Equation

\[ P_{i}^{k} = |(\vec{x}^{k} + \Delta \vec{x}^{k}) - (\vec{x}_i + \Delta \vec{x}_i)| + T_{i}^{k} + I_{i}^{k} + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{i}^{k} = |(\vec{x}^{k} + \Delta \vec{x}^{k}) - (\vec{x}_i + \Delta \vec{x}_i)| + T_{i}^{k} - I_{i}^{k} + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_{i}^{k} + \lambda^k \cdot \Delta \varphi_{i}^{k} \]

\( N_{i}^{k} \) phase ambiguity (one and the same for one pass)
Observation Equation

\[ P_{ki}^k = \left| (\vec{x}_{ki}^k + \Delta \vec{x}_{ki}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_{ki}^k + I_{ki}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ki}^k = \left| (\vec{x}_{ki}^k + \Delta \vec{\chi}_{ki}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_{ki}^k - I_{ki}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_{ki}^k + \lambda^k \cdot \Delta \varphi_{ki}^k \]

- \( N_{ki}^k \): phase ambiguity (one and the same for one pass)
- \( \Delta \varphi_{ki}^k \): initial phase shift between the oscillators at station i and satellite k
Dependency of the Terms

\[ P_{i}^{k} = \left| (\vec{x}_{k}^{k} + \Delta \vec{x}_{k}^{k}) - (\vec{x}_{i} + \Delta \vec{x}_{i}) \right| + T_{i}^{k} + I_{i}^{k} + c \cdot (\delta_{i} - a_{i}) - c \cdot (\delta^{k} - a^{k}) \]

\[ L_{i}^{k} = \left| (\vec{\chi}_{k}^{k} + \Delta \vec{\chi}_{k}^{k}) - (\vec{x}_{i} + \Delta \vec{\chi}_{i}) \right| + T_{i}^{k} - I_{i}^{k} + c \cdot (\delta_{i} - \alpha_{i}) - c \cdot (\delta^{k} - \alpha^{k}) \]

\[ + \lambda^{k} \cdot N_{i}^{k} + \lambda^{k} \cdot \Delta \phi_{i}^{k} \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or ...)

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Dependency of the Terms

\[ P_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i^i + \Delta \vec{x}_i^i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i^i + \Delta \vec{x}_i^i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)

Code
- \( \Delta \vec{x}_i \)

Phase
- \( \Delta \vec{\chi}_i \)
Dependency of the Terms

\[
P_i^k = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L_i^k = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
\]

\[+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k\]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)

- Code
  - \(\Delta \vec{x}_i\)
  - \(a_i\)

- Phase
  - \(\Delta \vec{\chi}_i\)
  - \(\alpha_i\)
Dependency of the Terms

\[ P_{ik}^k = |(\vec{x}_{ik} + \Delta \vec{x}_{ik}) - (\vec{x}_{ii} + \Delta \vec{x}_{ii})| + T_{ik}^k + I_{ik}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ik}^k = |(\vec{\chi}_{ik} + \Delta \vec{\chi}_{ik}) - (\vec{\chi}_{ii} + \Delta \vec{\chi}_{ii})| + T_{ik}^k - I_{ik}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_{ik}^k + \lambda^k \cdot \Delta \varphi_{ik}^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . . )

**Code**

- \( \Delta \vec{x}_i \)
- \( a_i \)
- \( \delta^k \)

**Phase**

- \( \Delta \vec{\chi}_i \)
- \( \alpha_i \)
- \( \delta^k \)
Dependency of the Terms

\[ P_{ki}^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_{ki}^k + I_{ki}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ki}^k = \left| (\vec{x}_i^k + \Delta \vec{\chi}_i^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_{ki}^k - I_{ki}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_{ki}^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .

<table>
<thead>
<tr>
<th>Code</th>
<th>ISB: Inter-System Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \vec{x}_i )</td>
<td>( a_i )</td>
</tr>
<tr>
<td>( \Delta \vec{\chi}_i )</td>
<td>( \alpha_i )</td>
</tr>
</tbody>
</table>

\[ \text{AIUB} \]

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Dependency of the Terms

\[ P_i^k = |(\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = |(\vec{x}_i^k + \Delta \vec{\chi}_i^k) - (\vec{\chi}_i + \Delta \vec{\chi}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \\
+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)
- Code: \[ \Delta \vec{x}_i, \ a_i, \ \delta^k \]
- Phase: \[ \Delta \vec{\chi}_i, \ \alpha_i, \ \delta^k \]

**ISB:** Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)
Dependency of the Terms

\[ P^k_i = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L^k_i = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or ...)

- Code: \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)
- Phase: \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \delta^k \)

**ISB:** Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or ...)

- Code: \( \Delta \vec{x}^k \)
- Phase: \( \Delta \vec{\chi}^k \)
Dependency of the Terms

$$P_{ik}^k = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_{ik}^k + I_{ik}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

$$L_{ik}^k = |(\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_{ik}^k - I_{ik}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)$$

$$+ \lambda^k \cdot N_{ik}^k + \lambda^k \cdot \Delta \varphi_{ik}^k$$

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)

- **Code**
  - \(\Delta \vec{x}_i\)
  - \(\alpha_i\)
  - \(\delta_i\)
  - ISB: Inter-System Bias

- **Phase**
  - \(\Delta \vec{\chi}_i\)
  - \(\alpha_i\)
  - \(\delta_i\)

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)

- **Code**
  - \(\Delta \vec{x}_i^k\)
  - \(\Delta \vec{x}_i\)

- **Phase**
  - \(\Delta \vec{\chi}_i^k\)
  - \(\Delta \vec{\chi}_i\)
Dependency of the Terms

\[ P_i^k = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = |(\vec{x}^k + \Delta \chi^k) - (\vec{x}_i + \Delta \chi_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)
- Code: \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)
- Phase: \( \Delta \chi_i \), \( \alpha_i \), \( \delta^k \)

**ISB:** Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)
- Code: \( \Delta \vec{x}^k \), \( \Delta \vec{x}_i \), \( a_i \)
- Phase: \( \Delta \chi^k \), \( \Delta \chi_i \), \( \alpha_i \)
Dependency of the Terms

\[ P_{ki}^k = |(\vec{x}_k^i + \Delta \vec{x}_k^i) - (\vec{x}_i + \Delta \vec{x}_i)| + T_{ki}^k + I_{ki}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ki}^k = |(\vec{x}_k^i + \Delta \vec{\chi}_k^i) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_{ki}^k - I_{ki}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_{ki}^k + \lambda^k \cdot \Delta \varphi_{ki}^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or ...)

- **Code**: \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)
- **Phase**: \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \delta^k \)

**ISB**: Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or ...)

- **Code**: \( \Delta \vec{x}_k^i \), \( \Delta \vec{x}_i^k \), \( a_i \), \( a^k \)
- **Phase**: \( \Delta \vec{\chi}_k^i \), \( \Delta \vec{\chi}_i^k \), \( \alpha_i \), \( \alpha^k \)
 Dependency of the Terms

\[
P_i^k = |(\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
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\[
L_i^k = |(\vec{x}_i^k + \Delta \vec{\chi}_i^k) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
\]
\[
+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k
\]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)
- Code: \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)  
- Phase: \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \delta^k \)  

**ISB:** Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)
- Code: \( \Delta \vec{x}_i^k \), \( \Delta \vec{x}_i \), \( a_i \), \( a^k \)  
- Phase: \( \Delta \vec{\chi}_i^k \), \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \alpha^k \)  

**IFB:** Inter-Frequency Bias
Dependency of the Terms

\[ P_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = \left| (\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or ...)

<table>
<thead>
<tr>
<th>Code</th>
<th>( \Delta \vec{x}_i )</th>
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<th>( \delta^k )</th>
<th>ISB: Inter-System Bias</th>
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<td>( \alpha_i )</td>
<td>( \delta^k )</td>
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**Frequency:** (f1 or f2 or fn for GLONASS or ...)

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**Signal type:** (C1W/C or C2W/C or L2W/C or ...)

Astronomical Institute, University of Bern
Dependency of the Terms

\[
P_{ik}^k = \left| (\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_{ik}^k + I_{ik}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
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\[
L_{ik}^k = \left| (\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_{ik}^k - I_{ik}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
+ \lambda^k \cdot N_{ik}^k + \lambda^k \cdot \Delta \varphi_{ik}^k
\]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)

- **Code:** \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)  
  ISB: Inter-System Bias
- **Phase:** \( \Delta \vec{x}_i \), \( \alpha_i \), \( \delta^k \)

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- **Code:** \( a_i \)
Dependency of the Terms

\[ P^k_i = \left| (\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i) \right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L^k_i = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

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- Code: \( \Delta \vec{x}_i \), \( a_i \), \( \delta^k \)
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**Signal type:** (C1W/C or C2W/C or L2W/C or ...)
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Dependency of the Terms

\[ P_{ik}^k = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ik}^k = |(\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{\chi}_i + \Delta \vec{\chi}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

The following parameters depend on:

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- **Phase:** \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \delta^k \)

**Frequency:** (f1 or f2 or fn for GLONASS or ...)
- **Code:** \( \Delta \vec{x}_i^k \), \( \Delta \vec{x}_i \), \( a_i \), \( a^k \) - IFB: Inter-Frequency Bias
- **Phase:** \( \Delta \vec{\chi}_i^k \), \( \Delta \vec{\chi}_i \), \( \alpha_i \), \( \alpha^k \)

**Signal type:** (C1W/C or C2W/C or L2W/C or ...)
- **Code:** \( a_i \), \( a^k \) - DCB: Differential Code Bias
### Dependency of the Terms

\[
P_i^k = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)
\]

\[
L_i^k = |(\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)
\]

\[
+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k
\]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)

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**ISB:** Inter-System Bias

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)

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**IFB:** Inter-Frequency Bias

**Signal type:** (C1W/C or C2W/C or L2W/C or . . .)

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<tr>
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**DCB:** Differential Code Bias

(Quarter cycle problem)
Dependency of the Terms

\[ P_{ki}^k = \left| (\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i^k + \Delta \vec{x}_i^k) \right| + T_{ik}^k + I_{ik}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta_k^k - a_k^k) \]

\[ L_{ki}^k = \left| (\vec{x}_k^k + \Delta \vec{\chi}_k^k) - (\vec{x}_i^k + \Delta \vec{\chi}_i^k) \right| + T_{ik}^k - I_{ik}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta_k^k - \alpha_k^k) + \lambda_k^k \cdot N_{ki}^k + \lambda_k^k \cdot \Delta \varphi_{ki}^k \]

The following parameters depend on:

**GNSS:** (GPS or GLONASS or . . .)
- Code: \( \Delta \vec{x}_i^k \), \( a_i \), \( \delta_k^k \) ISB: Inter-System Bias
- Phase: \( \Delta \vec{\chi}_i^k \), \( \alpha_i \), \( \delta_k^k \)

**Frequency:** (f1 or f2 or fn for GLONASS or . . .)
- Code: \( \Delta \vec{x}_i^k \), \( \Delta \vec{x}_i^k \), \( a_i \), \( a_k^k \) IFB: Inter-Frequency Bias
- Phase: \( \Delta \vec{\chi}_i^k \), \( \Delta \vec{\chi}_i^k \), \( \alpha_i \), \( \alpha_k^k \)

**Signal type:** (C1W/C or C2W/C or L2W/C or . . .)
- Code: \( a_i \), \( a_k^k \) DCB: Differential Code Bias
Dependency of the Terms

\[ P_i^k = |(\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = |(\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

**GNSS:**
- **Code**
  - \( \Delta \vec{x}_i \)
  - \( \Delta \vec{x}_i^k \)
- **Phase**
  - \( \alpha_i \)
  - \( \alpha_i^k \)

**Frequency:**
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  - \( \Delta \vec{x}_i \)
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- **Phase**
  - \( \alpha_i \)
  - \( \alpha_i^k \)

**Signal type:**
- **Code**
  - \( a_i \)
  - \( a_i^k \)

**Antenna**

**Hardware**

**ISB:** Inter-System Bias

**IFB:** Inter-Frequency Bias

**DCB:** Differential Code Bias
If we focus on processing code measurements we have to consider:
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- **DCB: differential code bias**
  different hardware delays for P- and C-Code
  bias at the receiver and satellite
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- **DCB: differential code bias**
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- **ISB: inter-system bias**
  different hardware delays for measurements of different GNSS
  bias only at the receiver
If we focus on processing code measurements we have to consider:

- **DCB: differential code bias**
  different hardware delays for P- and C-Code
  bias at the receiver and satellite

- **ISB: inter-system bias**
  different hardware delays for measurements of different GNSS
  bias only at the receiver

- **IFB: inter-frequency bias**
  frequency-dependent hardware delays for the different
  GLONASS-signals
  bias at the receiver
  (also at the satellite when frequency is changed)
GNSS Code Biases: Overview

Inter-frequency bias

IFB(P)

IFB(C/A)

Inter-system bias, ISB

? 

f_n: -7

f_n: 0

f_n: 6

GLONASS

P-Code

C/A-Code

GPS

P-Code

C/A-Code

Differential code bias, DCB(GLO)

Differential code bias, DCB(GPS)
We can only extract the sum of delays from a GPS/GLONASS data processing.
Why do we Need These Biases?

GPS Sat. $k$
Why do we Need These Biases?

GPS Sat. $k$

GPS rec.
Why do we Need These Biases?
Why do we Need These Biases?

GPS Sat. $k$

GPS rec. (C1W-Code)  GPS rec. (C1W-Code)
Why do we Need These Biases?

\[ \delta^k + a^k (C1W) \]

GPS Sat. \( k \)

GPS rec. (C1W-Code)

GPS rec. (C1W-Code)
Why do we Need These Biases?

GPS Sat.  

GPS rec.  (C1W-Code)

GPS rec.  (C1W-Code)

GPS rec.  (C1C-Code)

\[ \delta^k + a^k(C1W) \]

\[ \delta^k + a^k(C1W) \]
Why do we Need These Biases?

\[
\begin{align*}
\text{GPS Sat. } k & \\
\text{GPS rec. (C1W-Code)} & \\
\text{GPS rec. (C1W-Code)} & \\
\text{GPS rec. (C1C-Code)} & \\
\end{align*}
\]

\[
\begin{align*}
\text{GPS-sat clock} & \\
\delta^k + a^k(C1W) & \\
\text{GPS-sat clock} & \\
\delta^k + a^k(C1W) & \\
\text{GPS-sat clock} & \\
\delta^k + a^k(C1C) & \\
\end{align*}
\]
Why do we Need These Biases?

GPS Sat. $k$

GPS rec. (C1W-Code)

GPS-sat clock
$\delta^k + a^k(C1W)$

GPS rec. (C1W-Code)

GPS-sat clock
$\delta^k + a^k(C1W)$

GPS rec. (C1C-Code)

GPS-sat clock
$\delta^k + a^k(C1W) + DCB^k(C1W - C1C')$
Why do we Need These Biases?

Resulting satellite clock correction refers to C1W

\[
\delta^k + a^k(C1W) + DCB^k(C1W - C1C)
\]
Why do we Need These Biases?

Resulting satellite clock correction refers to C1C

$$\delta^k + a^k(C1C) + DCB^k(C1C - C1W)$$

GPS Sat. $k$

GPS rec. (C1W-Code)

GPS rec. (C1W-Code)

GPS rec. (C1C-Code)
Why do we Need These Biases?

Whether choosing C1W or C1C as reference is fully equivalent. Choosing C1C or C1W for the satellite clock is purely conventional. The IGS products refer to the P-Code for the satellite clocks.
Why do we Need These Biases?

\[ \begin{align*}
\text{GPS Sat. } & k \\
\text{GPS rec. } & k: \text{C2W-Code} \\
\text{GPS rec. } & k: \text{C2W-Code} \\
\text{GPS rec. } & k: \text{C2W-Code}
\end{align*} \]

\[ \begin{align*}
\text{GPS-sat clock } & k: \delta^k + a^k(C2W) \\
\text{GPS-sat clock } & k: \delta^k + a^k(C2W) \\
\text{GPS-sat clock } & k: \delta^k + a^k(C2W)
\end{align*} \]
Why do we Need These Biases?

\[
\begin{align*}
\text{GPS rec.} & \quad k: \text{C2W-Code} \\
\text{GPS Sat.} & \quad k \\
\text{GPS rec.} & \quad k: \text{C2W-Code} \\
\text{GPS Sat.} & \quad l \\
\text{GPS rec.} & \quad k: \text{C2W-Code} \\
\end{align*}
\]

\[
\begin{align*}
\text{GPS-sat clock} & \quad k: \delta^k + a^k(C2W) \\
\text{GPS-sat clock} & \quad k: \delta^k + a^k(C2W) \\
\text{GPS-sat clock} & \quad k: \delta^k + a^k(C2W) \\
\end{align*}
\]
Why do we Need These Biases?

GPS Sat. \(k\)  
GPS rec.  
\(k\): C2W-Code  
\(l\): C2W-Code

GPS Sat. \(l\)  
GPS rec.  
\(k\): C2W-Code  
\(l\): C2W-Code

**GPS-sat clock**  
\(k\): \(\delta^k + a^k(C2W)\)  
\(l\): \(\delta^l + a^l(C2W)\)
Why do we Need These Biases?

GPS Sat. \( k \)

GPS rec. \( k: \) C2W-Code
\( l: \) C2W-Code

GPS Sat. \( l \)

GPS rec. \( k: \) C2W-Code
\( l: \) C2C-Code

GPS sat clock
\( k: \delta^k + a^k(C2W) \)
\( l: \delta^l + a^l(C2W) \)

GPS sat clock
\( k: \delta^k + a^k(C2W) \)
\( l: \delta^l + a^l(C2C) \)
Why do we Need These Biases?

GPS Sat. $k$

GPS rec.

$k$: C2W-Code
$l$: C2W-Code

GPS-sat clock

$k$: $\delta^k + a^k(C2W)$
$l$: $\delta^l + a^l(C2W)$

GPS Sat. $l$

GPS rec.

$k$: C2W-Code
$l$: C2C-Code

GPS-sat clock

$k$: $\delta^k + a^k(C2W)$
$l$: $\delta^l + a^l(C2C)$
Why do we Need These Biases?

GPS Sat. \(k\)  

\[ \delta^k + a^k(C2W) \]

\[ \delta^l + a^l(C2W) + DCB^l(C2W - C2C) \]

GPS Sat. \(l\)  

\[ \delta^k + a^k(C2W) \]

\[ \delta^l + a^l(C2W) + DCB^l(C2W - C2C) \]

GPS rec. \(k\): C2W-Code  

GPS rec. \(l\): C2C-Code  

GPS rec. \(k\): C2W-Code  

GPS rec. \(l\): C2C-Code
Why do we Need These Biases?

GPS Sat. \( k \)

GPS Sat. \( l \)

GPS rec. \( k \): C2W-Code
GPS rec. \( l \): C2C-Code

GPS rec. \( k \): C2W-Code
GPS rec. \( l \): C2C-Code

GPS-rec clock
\( k \): \( \delta_1 + a_1(C'2W) \)
\( l \): \( \delta_1 + a_1(C'2W) \)

\( k \): \( \delta_2 + a_2(C2W) \)
\( l \): \( \delta_2 + a_2(C'2C) \)

\( k \): \( \delta_3 + a_3(C'2W) \)
\( l \): \( \delta_3 + a_3(C'2C) \)
Why do we Need These Biases?

GPS Sat. \( k \)

GPS Sat. \( l \)

GPS rec. \( k \): C2W-Code
GPS rec. \( l \): C2W-Code

GPS-rec clock
\( k \): \( \delta_1 + a_1(C2W) \)
\( l \): \( \delta_1 + a_1(C2W) \)

GPS-rec clock
\( k \): \( \delta_2 + a_2(C2W) \)
\( l \): \( \delta_2 + a_2(C2W) + DCB_2(C2W - C2C') \)

GPS-rec clock
\( k \): \( \delta_3 + a_3(C2W) \)
\( l \): \( \delta_3 + a_3(C2W) + DCB_3(C2W - C2C') \)
Code Biases in a GPS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1W-C1C or P1–C1 DCBs for all GPS satellites,
- C2W-C2C or P2–C2 DCBs for Block IIR-M (or later) satellites,
- C2W-C2C or P2–C2 DCBs for receivers if it tracks GPS satellites with P- and C-code on the second frequency at the same time.
Depending on the code measurements of the individual receivers we can get:

- $C1W-C1C$ or $P1-C1$ DCBs for all GPS satellites,
- $C2W-C2C$ or $P2-C2$ DCBs for Block IIR-M (or later) satellites,
- $C2W-C2C$ or $P2-C2$ DCBs for receivers if it tracks GPS satellites with P- and C-code on the second frequency at the same time.

As soon as we get a mixture between all these observation types in one network solution we need
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- C1W-C1C or P1—C1 DCBs for all GPS satellites,
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As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
Code Biases in a GPS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1W-C1C or P1–C1 DCBs for all GPS satellites,
- C2W-C2C or P2–C2 DCBs for Block IIR-M (or later) satellites,
- C2W-C2C or P2–C2 DCBs for receivers if it tracks GPS satellites with P- and C-code on the second frequency at the same time.

As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
- or to estimate DCB parameters
  
P1–C1: Your reference clock only belongs to either the P- or C/A-code class – you need an additional reference for the satellite related biases.
  
P2–C2: You have these DCBs at the satellites and receivers at the same time – you need additional references for the satellite and receiver related biases.
Why do we Need These Biases?

GLO Sat.  

GLO rec.  

$GLO-sat\ text{\ clock}$  

$k: \delta^k + a^k(C1P)$

GLO rec.  

$GLO-sat\ text{\ clock}$  

$k: \delta^k + a^k(C1P)$

GLO rec.  

$GLO-sat\ text{\ clock}$  

$k: \delta^k + a^k(C1P)$
Why do we Need These Biases?

GLO Sat. \( k \)  
- GLO rec. \( k \): C1P-Code
  - GLO-sat clock \( k \): \( \delta^k + a^k(C1P) \)

GLO Sat. \( l \)  
- GLO rec. \( k \): C1P-Code
  - GLO-sat clock \( k \): \( \delta^k + a^k(C1P) \)

GLO rec. \( k \): C1P-Code
  - GLO-sat clock \( k \): \( \delta^k + a^k(C1P) \)
Why do we Need These Biases?

GLO Sat. \(k\)

\[ \delta^k + a^k(C1P) \]

GLO Sat. \(l\)

\[ \delta^l + a^l(C1P) \]

GLO rec. \(k\): C1P-Code

GLO rec. \(k\): C1P-Code

GLO rec. \(k\): C1P-Code

GLO-sat clock

GLO-sat clock

GLO-sat clock
Why do we Need These Biases?

GLO Sat. \( k \)

GLO Sat. \( l \)

GLO rec. \( k \): C1P-Code

GLO rec. \( l \): C1P-Code

GLO-sat clock

\[ k: \delta^k + a^k(C1P) \]

\[ l: \delta^l + a^l(C1P) \]
Why do we Need These Biases?

GLO Sat. $k$

GLO rec.

$k$: C1P-Code
$l$: C1P-Code

GLO dec. clock

$k$: $\delta^k + a^k(C1P)$
$l$: $\delta^l + a^l(C1P)$

GLO Sat. $l$

GLO rec.

$k$: C1P-Code
$l$: C1P-Code

GLO dec. clock

$k$: $\delta^k + a^k(C1P)$
$l$: $\delta^l + a^l(C1P)$
Why do we Need These Biases?

GLO Sat. $k$

GLO rec.
$k$: C1P-Code
$l$: C1P-Code

GLO Sat. $l$

GLO rec.
$k$: C1P-Code
$l$: C1P-Code

GLO-sat clock
$k$: $\delta^k + a^k(C1P)$
$l$: $\delta^l + a^l(C1P)$

GLO-sat clock
$k$: $\delta^k + a^k(C1P)$
$l$: $\delta^l + a^l(C1P)$

GLO-sat clock
$k$: $\delta^k + a^k(C1P)$
$l$: $\delta^l + a^l(C1P)$
Why do we Need These Biases?

GLO Sat. \( k \)

GLO rec. \( k \): C1P-Code

GLO rec. \( l \): C1P-Code

GLO Sat. \( l \)

GLO rec. \( k \): C1C-Code

GLO rec. \( l \): C1C-Code

GLO-sat clock

\( k \): \( \delta^k + a^k(C1P) \)

\( l \): \( \delta^l + a^l(C1P) \)

GLO-sat clock

\( k \): \( \delta^k + a^k(C1C) \)

\( l \): \( \delta^l + a^l(C1C) \)

GLO-sat clock

\( k \): \( \delta^k + a^k(C1C) \)

\( l \): \( \delta^l + a^l(C1C) \)
Why do we Need These Biases?

GLO Sat.  \( k \)

GLO Sat.  \( l \)

GLO rec.  \( k \): C1P-Code
GLO rec.  \( l \): C1P-Code

GLO rec.  \( k \): C1C-Code
GLO rec.  \( l \): C1C-Code

GLO-sat clock
\[ k: \delta^k + a^k(C1P) \]
\[ l: \delta^l + a^l(C1P) \]

GLO-sat clock
\[ k: \delta^k + a^k(C1P) + DCB^k(C1P - C1C) \]
\[ l: \delta^l + a^l(C1P) + DCB^l(C1P - C1C) \]
Why do we Need These Biases?

GLO Sat. \(k\)  
GLO Sat. \(l\)  

GLO rec.  
\(k\): C1P-Code  
\(l\): C1P-Code  

GLO rec.  
\(k\): C1C-Code  
\(l\): C1C-Code  

GLO rec.  
\(k\): C1C-Code  
\(l\): C1C-Code  

GLO-rec clock  
\(k\): \(\delta_1 + a_1(C1P)\)  
\(l\): \(\delta_1 + a_1(C1P)\)  

GLO-rec clock  
\(k\): \(\delta_2 + a_2(C1C')\)  
\(l\): \(\delta_2 + a_2(C1C')\)  

GLO-rec clock  
\(k\): \(\delta_3 + a_3(C1C')\)  
\(l\): \(\delta_3 + a_3(C1C')\)
Why do we Need These Biases?

GLO Sat. $k$
- GLO rec. $k$: C1P-Code
- GLO rec. $l$: C1P-Code

GLO Sat. $l$
- GLO rec. $k$: C1C-Code
- GLO rec. $l$: C1C-Code

GLO-rec clock
- $k$: $\delta_1 + a_1(C1P)^k$
- $l$: $\delta_1 + a_1(C1P)^l$

GLO-rec clock
- $k$: $\delta_2 + a_2(C1C)^k$
- $l$: $\delta_2 + a_2(C1C)^l$

GLO-rec clock
- $k$: $\delta_3 + a_3(C1C)^k$
- $l$: $\delta_3 + a_3(C1C)^l$
Why do we Need These Biases?

Because each GLONASS satellite emits the signal on its own frequency, the receiver hardware delays become (satellite-)frequency-dependent.
Code Biases in a GLONASS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1P−C1C or P1−C1 DCBs for all GLONASS satellites,
- C2P−C2C or P2−C2 DCBs for all GLONASS satellites.
Code Biases in a GLONASS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1P–C1C or P1–C1 DCBs for all GLONASS satellites,
- C2P–C2C or P2–C2 DCBs for all GLONASS satellites.

As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
- or to estimate DCB parameters P1–C1 and P2–C2: Your reference clock only belongs to either the P- or C-code class – you need an additional reference for the satellite related biases.
Code Biases in a GLONASS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1P−C1C or P1−C1 DCBs for all GLONASS satellites,
- C2P−C2C or P2−C2 DCBs for all GLONASS satellites.

As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
- or to estimate DCB parameters P1−C1 and P2−C2: Your reference clock only belongs to either the P- or C-code class – you need an additional reference for the satellite related biases.

We also need to consider in addition an inter-frequency bias (IFB) because each GLONASS satellite emits the signal on another frequency.
Why do we Need These Biases?

GPS Sat. $k$

GPS rec. $k$: C1W-Code

GNSS rec. $k$: C1W-Code

GNSS rec. $k$: C1C-Code
Why do we Need These Biases?

GPS Sat. \( k \)

GLO Sat. \( l \)

GPS rec. \( k: \) C1W-Code

GNSS rec. \( k: \) C1W-Code

GNSS rec. \( k: \) C1C-Code
Why do we Need These Biases?

GPS Sat. \( k \)  
- \( k \): C1W-Code

GLO Sat. \( l \)  
- \( k \): C1W-Code
- \( l \): C1P-Code

GPS rec. \( k \)  
- \( k \): C1W-Code

GNSS rec. \( k \)  
- \( k \): C1W-Code

GNSS rec. \( l \)  
- \( l \): C1C-Code

GNSS rec. \( l \)  
- \( l \): C1C-Code
Why do we Need These Biases?

GPS Sat. \(k\)

- GPS rec. \(k\): C1W-Code
- GNSS rec. \(k\): C1W-Code
- GNSS rec. \(l\): C1P-Code

GLO Sat. \(l\)

- GNSS rec. \(k\): C1C-Code
- GNSS rec. \(l\): C1C-Code

\[\text{GNSS-sat clock} \quad k: \delta^k + a^k(C1W)\]
\[\text{GNSS-sat clock} \quad l: \delta^k + a^k(C1P)\]
Why do we Need These Biases?

**GPS Sat.**
- $k$: C1W-Code
- GNSS rec. $k$: C1W-Code
- GNSS rec. $l$: C1C-Code
- GNSS-sat clock $k$: $\delta^k + a^k(C1W)$
- GNSS-sat clock $l$: $\delta^l + a^l(C1P)$

**GLO Sat.**
- $l$: C1P-Code
- GNSS rec. $k$: C1C-Code
- GNSS rec. $l$: C1C-Code
- GNSS-sat clock $k$: $\delta^k + a^k(C1W) + DCB^k(C1W - C1C)$
- GNSS-sat clock $l$: $\delta^l + a^l(C1P) + DCB^l(C1P - C1C)$
Why do we Need These Biases?

GPS Sat. \( k \):
- GNSS-rec clock
  - \( k: \delta_1 + a_1(C1W) \)

GLO Sat. \( l \):
- GNSS-rec clock
  - \( k: \delta_2 + a_2(C1W)^{GPS} \)
  - \( l: \delta_2 + a_2(C1P)^{GLO} \)

GNSS-rec clock
- \( k: \delta_3 + a_3(C1C)^{GPS} \)
- \( l: \delta_3 + a_3(C1C)^{GLO} \)
Why do we Need These Biases?

GPS Sat. \( k \)

GPS rec. \( k \): C1W-Code

GNSS rec. \( k \): C1W-Code

GNSS rec. \( l \): C1C-Code

GLO Sat. \( l \)

GNSS rec. \( k \): C1W-Code

\( \delta_1 + a_1(C1W) \)

\( \delta_2 + a_2(C1W)^{GPS} \)

\( \delta_2 + a_2(C1P)^{GPS} + ISB_2(C1P)^{GPS-GLO} \)

\( \delta_3 + a_3(C1C)^{GPS} \)

\( \delta_3 + a_3(C1C)^{GPS} + ISB_3(C1C)^{GPS-GLO} \)

GNSS-rec clock

GNSS-rec clock

GNSS-rec clock
Why do we Need These Biases?

\[ \text{GPS Sat. } k \]
\[ \text{GLO Sat. } l \]

\[ \text{GPS rec. } k: \text{ C1W-Code} \]
\[ \text{GNSS rec. } k: \text{ C1W-Code} \]
\[ \text{GNSS rec. } l: \text{ C1P-Code} \]

\[ \text{GNSS-rec clock } k: \delta_1 + a_1(C1W) \]
\[ \text{GNSS-rec clock } k: \delta_2 + a_2(C1W)^{GPS} \]
\[ \text{GNSS-rec clock } l: \delta_2 + a_2(C1P)^{GPS} + ISB_2(C1P)^{GPS\text{-GLO}} \]
\[ \text{GNSS-rec clock } k: \delta_3 + a_3(C1C)^{GPS} \]
\[ \text{GNSS-rec clock } l: \delta_3 + a_3(C1C)^{GPS} + ISB_3(C1C)^{GPS\text{-GLO}} \]
Biases in a GPS/GLONASS Network Solution

We can see all DCBs from a GPS and GLONASS network solution and the GLONASS IFB in a combine GPS/GLONASS network solution.
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We need to consider in addition an inter-system bias (ISB) at each combined GPS/GLONASS receiver.
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All these biases are hardware related (with respect to the satellites or receivers). Consequently we can only assess them as one single parameter

\[ a_i = DCB + IFB + ISB. \]
Biases in a GPS/GLONASS Network Solution

We can see all DCBs from a GPS and GLONASS network solution and the GLONASS IFB in a combine GPS/GLONASS network solution.

We need to consider in addition an inter-system bias (ISB) at each combined GPS/GLONASS receiver.

All these biases are hardware related (with respect to the satellites or receivers). Consequently we can only assess them as one single parameter

\[ a_i = DCB + IFB + ISB. \]

References are needed for

- P1-C1 DCB for GPS satellites,
- P2-C2 DCB for GPS satellites and GPS receivers tracking C2C,
- ISB for combined GPS/GLONASS tracking receivers,
- IFB for GLONASS tracking receivers.
In consequence the estimated biases depend on the realization of the reference (e.g., selection of a reference or list of stations in case of zero-mean conditions).
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These biases need to be considered (estimated or corrected) at any time when different types of code measurements are involved.
Biases in a GPS/GLONASS Network Solution

In consequence the estimated biases depend on the realization of the reference (e.g., selection of a reference or list of stations in case of zero-mean conditions).

These biases need to be considered (estimated or corrected) at any time when different types of code measurements are involved.

Typical examples are:

- Receiver/satellite clock estimation in a zero-difference network solution.
- Melbourne-Wübbena linear combination for ambiguity resolution (even in the double-difference analysis).
IFB/ISB Comparisons

ISB characteristic of the receivers

IFB/ISB computed by CODE

Test solution submitted to the IGS workshop on GNSS biases in January 2012
IFB/ISB Comparisons

ISB characteristic of the receivers

IFB/ISB computed by GFZ

Test solution submitted to the IGS workshop on GNSS biases in January 2012
IFB/ISB Comparisons

ISB characteristic of the receivers

IFB/ISB computed by ESA

Test solution submitted to the IGS workshop on GNSS biases in January 2012
Differences between ISB characteristic of the receivers

IFB/ISB computed by COD–GFZ

Test solution submitted to the IGS workshop on GNSS biases in January 2012
IFB/ISB Comparisons

Differences between ISB characteristic of the receivers

IFB/ISB computed by COD–ESA

Test solution submitted to the IGS workshop on GNSS biases in January 2012
IFB/ISB Comparisons

Differences between ISB characteristic of the receivers

IFB/ISB computed by GFZ–ESA

Test solution submitted to the IGS workshop on GNSS biases in January 2012
### IFB/ISB Comparisons

**Differences between ISB characteristic of the receivers**

<table>
<thead>
<tr>
<th>Difference</th>
<th>Num. of Stations</th>
<th>Mean in ns</th>
<th>Median in ns</th>
<th>RMS in ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE – GFZ</td>
<td>52</td>
<td>-210.6</td>
<td>-209.4</td>
<td>4.9</td>
</tr>
<tr>
<td>CODE – ESA</td>
<td>39</td>
<td>-377.5</td>
<td>-377.6</td>
<td>5.1</td>
</tr>
<tr>
<td>GFZ – ESA</td>
<td>36</td>
<td>-167.7</td>
<td>-168.2</td>
<td>6.1</td>
</tr>
<tr>
<td>CODE – GRGS</td>
<td>50</td>
<td>-371.9</td>
<td>-372.2</td>
<td>18.7</td>
</tr>
<tr>
<td>GFZ – GRGS</td>
<td>46</td>
<td>-162.1</td>
<td>-163.0</td>
<td>19.2</td>
</tr>
<tr>
<td>ESA – GRGS</td>
<td>34</td>
<td>6.1</td>
<td>5.8</td>
<td>20.6</td>
</tr>
</tbody>
</table>

- High consistency (low RMS) with a proper IFB–handling (enough weight for the code measurements?)
- Test whether the ACs select the same type of code observations (CODE differs from ESA and GFZ)
Further Code Biases

- When forming linear combinations from the P1 and P2 measurements

\[ LC = \kappa_1 \cdot P_1 + \kappa_2 \cdot P_2 \]

the original P1–C1, P2–C2 DCB values have to be applied with the corresponding coefficients:

\[ DCB(LC) = \kappa_1 \cdot DCB(P1 - C1) + \kappa_2 \cdot DCB(P2 - C2) \]

- Alternative factors need to apply when P2 or C2 is not directly tracked (e.g., cross-correlation technique).
Further Code Biases

- When forming linear combinations from the P1 and P2 measurements

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- When extracting the ionosphere information by a linear combination, the differences between the hardware delays for P1 and P2 at the receiver and satellite need to be considered as an additional type of DCBs: \( DCB(P1-P2) \)
Further Code Biases

• When forming **linear combinations** from the P1 and P2 measurements

\[ LC = \kappa_1 \cdot P_1 + \kappa_2 \cdot P_2 \]

the original P1–C1, P2–C2 DCB values have to be applied with the corresponding coefficients:

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• Alternative factors need to apply when P2 or C2 is not directly tracked (e.g., cross-correlation technique).

• When extracting the **ionosphere information** by a linear combination, the differences between the hardware delays for P1 and P2 at the receiver and satellite need to be considered as an additional type of DCBs: \( DCB(P1-P2) \)

• With more GNSS and their new signals **more groups of Code Biases** will become relevant (e.g., third frequency for GPS and GLONASS).
Why do we Need These Biases?

GPS Sat. $k$  

GPS Sat. $l$  

GPS rec. $k$: C2W-Code  
GPS rec. $l$: C2W-Code  

GPS rec. $k$: C2W-Code  
GPS rec. $l$: C2C-Code
Why do we Need These Biases?

GPS Sat. \( k \)

GPS rec. \( k \): C2W-Code
\( l \): C2W-Code
\( l \): C2W-Code

GPS Sat. \( l \)

GPS rec. \( k \): C2W-Code
\( l \): C2C-Code
\( l \): C5Q-Code

GPS rec. \( k \): C2W-Code
\( l \): C2C-Code
\( l \): C5Q-Code
Why do we Need These Biases?

GPS Sat. \( k \)

GPS rec.
- \( k \): C2W-Code
- \( l \): C2W-Code

GPS Sat. \( l \)

GPS rec.
- \( k \): C2W-Code
- \( l \): C2C-Code
- \( l \): C5Q-Code

GPS rec.
- \( k \): C2W-Code
- \( l \): C2C-Code
- \( l \): C5Q-Code
- \( l \): C5I-Code
Why do we Need These Biases?

GPS Sat. $k$

GPS rec. $k$: C2W-Code
$l$: C2W-Code

GPS Sat. $l$

GPS rec. $k$: C2W-Code
$l$: C2C-Code
$l$: C5Q-Code
$l$: C5I-Code
$l$: C5X-Code
Why do we Need These Biases?

GPS Sat. \( k \)

<table>
<thead>
<tr>
<th>GPS rec.</th>
<th>( k ): C2W-Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( l ): C2W-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C2W-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C2W-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C2W-Code</td>
</tr>
</tbody>
</table>

GPS Sat. \( l \)

<table>
<thead>
<tr>
<th>GPS rec.</th>
<th>( k ): C2W-Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( l ): C2C-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C5Q-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C5I-Code</td>
</tr>
<tr>
<td></td>
<td>( l ): C5X-Code</td>
</tr>
</tbody>
</table>

R. Dach: Biases in Multi-GNSS Processing

Astronomical Institute, University of Bern
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ \text{DCB}^l(C2C - C2W), \text{DCB}^l(C5Q - C2W), \]
\[ \text{DCB}^l(C5I - C2W), \text{DCB}^l(C5X - C2W), \ldots \]
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ DCB^l(C2C - C2W), \quad DCB^l(C5Q - C2W), \]
\[ DCB^l(C5I - C2W), \quad DCB^l(C5X - C2W), \ldots \]

Remarks on these DCBs:

- No antenna calibration values for L5 are available.
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ DCB_l(C2C - C2W), \quad DCB_l(C5Q - C2W), \]
\[ DCB_l(C5I - C2W), \quad DCB_l(C5X - C2W), \ldots \]

Remarks on these DCBs:

- No antenna calibration values for L5 are available.
- The difference between C5 and C2 DCBs are not stable in time, see Montenbruck et al. 2012.
- \( DCB_l(C5I - C5Q) \) are expected to be as stable as \( DCB_l(C2C - C2W) \).
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

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\[ DCB^l(C5I - C2W), \quad DCB^l(C5X - C2W), \ldots \]

Remarks on these DCBs:

- No antenna calibration values for L5 are available.
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- \( DCB^l(C5I - C5Q) \) are expected to be as stable as \( DCB^l(C2C - C2W) \).
- C5X is a mixture of C5Q- and C5I-signal that is not further specified by the manufacturers.
  It must be expected that it is different for receivers from different manufacturers (firmware?).
If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ DCB^l(C2C - C2W), \ DCB^l(C5Q - C2W), \ DCB^l(C5I - C2W), \ DCB^l(C5X - C2W), \ldots \]

Questions/potential problems:

- What to do if \textit{C2W is not tracked} by any station in the network?
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ DCB^l(C2C - C2W), \quad DCB^l(C5Q - C2W), \]
\[ DCB^l(C5I - C2W), \quad DCB^l(C5X - C2W), \ldots \]

Questions/potential problems:

- What to do if \( C2W \) is not tracked by any station in the network?

- Be careful when redefining the DCBs:
  The different DCBs are dependent from each other:
  \[ DCB^l(C5I - C5Q) = DCB^l(C5I - C2W) - DCB^l(C5Q - C2W). \]
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[
\begin{align*}
DCB^l(C2C - C2W), & \quad DCB^l(C5Q - C2W), \\
DCB^l(C5I - C2W), & \quad DCB^l(C5X - C2W), \ldots
\end{align*}
\]

Questions/potential problems:

- What to do if \textit{C2W} is not tracked by any station in the network?

- Be careful when redefining the DCBs:
  The \textit{different DCBs are dependent} from each other:

\[
DCB^l(C5I - C5Q) = DCB^l(C5I - C2W) - DCB^l(C5Q - C2W).
\]

- Please be reminded that also receiver DCBs may be relevant.
Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

\[ DCB_l(C_2C - C_2W), \quad DCB_l(C_5Q - C_2W), \]
\[ DCB_l(C_5I - C_2W), \quad DCB_l(C_5X - C_2W), \ldots \]

Questions/potential problems:

- What to do if \( C_2W \) is not tracked by any station in the network?

- Be careful when redefining the DCBs:
  The different DCBs are dependent from each other:
  \[ DCB_l(C_5I - C_5Q) = DCB_l(C_5I - C_2W) - DCB_l(C_5Q - C_2W). \]

- Please be reminded that also receiver DCBs may be relevant.

- **It is urgently time to look for an alternative concept!**
Bias Handling in a Multi-GNSS Environment

\[ P_{ki}^k = \left| (\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i^i + \Delta \vec{x}_i^i) \right| + T_{ki}^k + I_{ki}^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ki}^k = \left| (\vec{x}_k^k + \Delta \chi_k^k) - (\vec{x}_i^i + \Delta \chi_i^i) \right| + T_{ki}^k - I_{ki}^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda_k \cdot N_{ki}^k + \lambda_k \cdot \Delta \varphi_{ki}^k \]

Each code measurement \( P_{ki}^k \) refers to two hardware delay terms: \( a_i \) for the receiver and \( a_k^k \) for the satellite.
Bias Handling in a Multi-GNSS Environment

\[
P^k_i = |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_i + \Delta \bar{x}_i)| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - \alpha^k)
\]

\[
L^k_i = |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_i + \Delta \bar{x}_i)| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \\
+ \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i
\]

Each code measurement \( P^k_i \) refers to two hardware delay terms: \( a_i \) for the receiver and \( \alpha^k \) for the satellite.

They can directly be setup as **pseudo-absolute code biases (OSB)** parameter.
Bias Handling in a Multi-GNSS Environment

\[ P_{ik}^k = |(\vec{x}^k + \Delta x^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_{ik}^k = |(\vec{x}^k + \Delta \chi^k) - (\vec{x}_i + \Delta \chi_i)| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

Each code measurement \( P_{ik}^k \) refers to two hardware delay terms: \( a_i \) for the receiver and \( a^k \) for the satellite.

They can directly be setup as pseudo-absolute code biases (OSB) parameter.

When processing linear combinations of the original observations each observation contributes to four OSB parameters.
Pseudo-Absolute Code Biases

Pseudo-absolute code biases parameter can be derived in all processing steps where also classical DCB parameters can be obtained:

- GNSS clock estimation
- GNSS ionosphere model generation
Pseudo-Absolute Code Biases

Pseudo-absolute code biases parameter can be derived in all processing steps where also classical DCB parameters can be obtained:

- GNSS clock estimation
- GNSS ionosphere model generation
- Melbourne-Wübben linear combination for ambiguity resolution
Pseudo-Absolute Code Biases

Pseudo-absolute code biases parameter can be derived in all processing steps where also classical DCB parameters can be obtained:

- GNSS clock estimation
- GNSS ionosphere model generation
- Melbourne-Wübbena linear combination for ambiguity resolution
- directly from the RINEX observations
  - if either redundant measurements (e.g., C1W and C1C) are provided, or
  - if an ionosphere model is introduced (take care on consistency).
Pseudo-Absolute Code Biases

Pseudo-absolute code biases parameter can be derived in all processing steps where also classical DCB parameters can be obtained:

- GNSS clock estimation
- GNSS ionosphere model generation
- Melbourne-Wübben linear combination for ambiguity resolution
- directly from the RINEX observations
  - if either redundant measurements (e.g., C1W and C1C) are provided, or
  - if an ionosphere model is introduced (take care on consistency).

Contributions from these sources can even be combined into one system of OSB parameters.
Pseudo-Absolute Code Biases: CLK

GPS

Satellite

G10

G02

C1C C1W C2W

C1C C1W C2W C2C C5Q

Receiver

C1C C1W C2W C2C
Pseudo-Absolute Code Biases: CLK

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Pseudo-Absolute Code Biases: CLK

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]
Pseudo-Absolute Code Biases: CLK

\[ \kappa_1 \cdot \text{C1W} + \kappa_2 \cdot \text{C2W} \]

\[ \kappa_1 \cdot \text{C1W} + \kappa_2 \cdot \text{C2W} \]
Pseudo-Absolute Code Biases: CLK

GPS

G10

G02

GLONASS

R01

R02

Satellite

Receiver

$\kappa_1 \cdot C_1 W + \kappa_2 \cdot C_2 W$

$\kappa_1 \cdot C_1 W + \kappa_2 \cdot C_2 W$
Pseudo-Absolute Code Biases: CLK

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]

GPS

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]

GLONASS

\[ \kappa_1 \cdot C_{1P} + \kappa_2 \cdot C_{2P} \]
Pseudo-Absolute Code Biases: CLK

\[
\kappa_1 \cdot C1W + \kappa_2 \cdot C2W
\]
Pseudo-Absolute Code Biases: CLK

\[
\kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \\
\kappa_1 \cdot C_{1P} + \kappa_2 \cdot C_{2P}
\]
Pseudo-Absolute Code Biases: CLK

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]

\[ \kappa_1 \cdot C_{1P} + \kappa_2 \cdot C_{2P} \]
Pseudo-Absolute Code Biases: CLK

\[ \kappa_1 \cdot C_{1W} + \kappa_2 \cdot C_{2W} \]
Pseudo-Absolute Code Biases: CLK

\[
\kappa_1 \cdot C1W + \kappa_2 \cdot C2W
\]

\[
\kappa_1 \cdot C1W + \kappa_2 \cdot C2W
\]
Pseudo-Absolute Code Biases: CLK+ION

GPS

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<thead>
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<th>Receiver</th>
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<tbody>
<tr>
<td>G10</td>
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<td></td>
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GLONASS

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Pseudo-Absolute Code Biases: CLK+ION

GPS

- G10: C1C, C1W, C2W
- G02: C1C, C1W, C2W, C2C, C5Q

GLONASS

- R01: C1P, C2P, C2C
- R02: C1P, C2P, C2C

Satellite

- C1C
- C1W
- C2W

Receiver
Pseudo-Absolute Code Biases

Estimated bias parameters from the CODE MGEX solution

Bias solution for GPS satellites based only on CLK:
reference ionosphere-free linear combination from C1W/C2W
(only biases for the satellites have been estimated)
Estimated bias parameters from the CODE MGEX solution

Bias solution for GPS satellites based only on CLK+ION: reference C1W
(also biases for all stations are estimated)
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(\lambda C_{ion\_free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(\text{LC}_{\text{ion-free}}) = \kappa_1 \cdot a(P1 - \text{Code}) + \kappa_2 \cdot a(P2 - \text{Code}) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{\text{ion-free}}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1W/C2W: no correction
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1W/C2W: no correction
- Receiver is tracking C1C/C2W: DCB(P1−C1) need to be applied

\[ \kappa_1 \cdot DCB(P1 - C1) = \frac{f_1^2}{f_1^2 - f_2^2} \cdot DCB(P1 - C1) \]
The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1C/C2D = L1(C/A) + (P2 - P1):
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:
- Receiver is tracking C1C/C2D = L1(C/A) + (P2 − P1):
  - Correction for the second frequency:
    \[ DCB(P2 - C1) \]
    \[ L1(C/A) \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1C/C2D = L1(C/A) + (P2 - P1):
  - Correction for the second frequency:

\[
\underbrace{DCB(P1 - C1)} - \underbrace{DCB(P1 - P2)}_{L1(C/A)}
\]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

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If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1C/C2D=L1(C/A)+\((P2-P1)\):
  - Correction for the second frequency:
    \[
    DCB(P1 - C1) - DCB(P1 - P2) + 0 \]
    \[
    L1(C/A) \]
    \[
    P2 \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

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Examples:
- Receiver is tracking \( C1C/C2D=L1(C/A) + (P2−P1) \):
  - Correction for the second frequency:
    \[ \underbrace{DCB(P1 - C1)}_{L1(C/A)} - \underbrace{DCB(P1 - P2)}_{P2} + 0 - \underbrace{DCB(P2 - P1)}_{P1} \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:
- Receiver is tracking $C1C/C2D=L1(C/A)+(P2-P1)$:
  - Correction for the second frequency:
    \[ DCB(P1 - C1) - DCB(P1 - P2) + 0 + DCB(P1 - P2) \]
    \[ L1(C/A) \]
    \[ P2 \]
    \[ P1 \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:
- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  - Correction for the second frequency:
    \[ DCB(P1 - C1) - DCB(P1 - P2) + 0 + DCB(P1 - P2) \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - \text{Code}) + \kappa_2 \cdot a(P2 - \text{Code}) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:
• Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  • Correction for the second frequency:
    \[ DCB(P1 - C1) \]
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking \( C1C/C2D = L1(C/A) + (P2 - P1) \):
  - Correction for the second frequency: DCB\((P1 - C1)\)
  - Correction for the first frequency: DCB\((P1 - C1)\)
Estimation of Code Biases

The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:
- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  - Correction for the second frequency: DCB(P1−C1)
  - Correction for the first frequency: DCB(P1−C1)
  - Combining the corrections from the two frequencies:
    \[ \kappa_1 \cdot DCB(P1 - C1) + \kappa_2 \cdot DCB(P1 - C1) \]
The Reference signal for IGS products is defined by:

\[ a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code) \]

If a receiver provides alternative measurements, DCB corrections need to be applied.

Examples:

- Receiver is tracking C1C/C2D=L1(C/A)+(P2-P1):
  - Correction for the second frequency: DCB(P1−C1)
  - Correction for the first frequency: DCB(P1−C1)
  - Combining the corrections from the two frequencies:
    \[ \kappa_1 \cdot DCB(P1 - C1) + \kappa_2 \cdot DCB(P1 - C1) = DCB(P1 - C1) \]
Estimation of Code Biases

When estimating DCBs the receiver classes must be distinguished as derived before:

- Receiver is tracking C1W/C2W:
  \[ 0 \cdot DCB(P_1 - C_1) \]

- Receiver is tracking C1C/C2W:
  \[ \kappa_1 \cdot DCB(P_1 - C_1) \]

- Receiver is tracking C1C/C2D = L1(C/A) + (P_2 - P_1):
  \[ 1 \cdot DCB(P_1 - C_1) \]
Estimation of Code Biases

When estimating DCBs the receiver classes must be distinguished as derived before:

- Receiver is tracking C1W/C2W:
  \[ 0 \cdot DCB(P_1 - C_1) \]

- Receiver is tracking C1C/C2W:
  \[ \kappa_1 \cdot DCB(P_1 - C_1) \]

- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  \[ 1 \cdot DCB(P_1 - C_1) \]

In order to estimate the \( DCB(P_1 - C_1) \), the factors are used as partial derivatives in the least squares adjustment process.
Estimation of Code Biases

When estimating DCBs the receiver classes must be distinguished as derived before:

- Receiver is tracking C1W/C2W:
  \[ 0 \cdot DCB(P1 - C1) \]

- Receiver is tracking C1C/C2W:
  \[ \kappa_1 \cdot DCB(P1 - C1) \]

- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  \[ 1 \cdot DCB(P1 - C1) \]

If the \( DCB(P1−C1) \) is known the pre-factor can be estimated and the tracking technology of the receiver can be detected/verified.
## Estimation of Code Biases

<table>
<thead>
<tr>
<th>Station</th>
<th>Estimated factor</th>
<th>Sigma</th>
<th>Related tracking</th>
<th>Receiver</th>
<th>Receiver tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>GANP</td>
<td>11515 M001</td>
<td>2.826</td>
<td>0.021</td>
<td>C1/P2</td>
<td>TRIMBLE NETR8</td>
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<tr>
<td>HERT</td>
<td>13212 M010</td>
<td>2.503</td>
<td>0.019</td>
<td>C1/P2</td>
<td>LEICA GRX1200GGPRO</td>
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<tr>
<td>J0Z2</td>
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<td>2.489</td>
<td>0.024</td>
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With the same technology the signal reported in the RINEX3 files for the MGEX stations can be verified and potentially the reference for the “X-signal” for each receiver type (and firmware) determined.
\[ P^k_i = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i + I^k_i + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L^k_i = |(\vec{x}^k + \Delta \vec{x}^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T^k_i - I^k_i + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \]

\[ + \lambda^k \cdot N^k_i + \lambda^k \cdot \Delta \varphi^k_i \]
On the first view, the phase bias parameters $(\alpha_i, \alpha^k)$ seems to be easily manageable in the GNSS processing because the ambiguity term $(N^k_i)$ is fully correlated and can absorb all effects.
On the first view, the phase bias parameters ($\alpha_i, \alpha^k$) seem to be easily manageable in the GNSS processing because the ambiguity term ($N^k_i$) is fully correlated and can absorb all effects.

This is only true as long as the ambiguities are not resolved to their integer values.
\[ L_i^k = \left| \vec{x}_i^k + \Delta \vec{\chi}_i^k \right| - \left| \vec{x}_i + \Delta \vec{\chi}_i \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) \\
\quad + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

\[ L_j^k = \left| \vec{x}_j^k + \Delta \vec{\chi}_j^k \right| - \left| \vec{x}_j + \Delta \vec{\chi}_j \right| + T_j^k - I_j^k + c \cdot (\delta_j - \alpha_j) - c \cdot (\delta^k - \alpha^k) \\
\quad + \lambda^k \cdot N_j^k + \lambda^k \cdot \Delta \varphi_j^k \]
Forming Differences

\[ L_i^k = \left| (\vec{x}_i^k + \Delta \vec{X}_i^k) - (\vec{x}_i + \Delta \vec{X}_i) \right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta_i^k - \alpha_i^k) \]
\[ + \lambda_i^k \cdot N_i^k + \lambda_i^k \cdot (\vec{\varphi}_i^k(t_0) - \vec{\varphi}_i(t_0)) \]

\[ L_j^k = \left| (\vec{x}_j^k + \Delta \vec{X}_j^k) - (\vec{x}_j + \Delta \vec{X}_j) \right| + T_j^k - I_j^k + c \cdot (\delta_j - \alpha_j) - c \cdot (\delta_j^k - \alpha_j^k) \]
\[ + \lambda_j^k \cdot N_j^k + \lambda_j^k \cdot (\vec{\varphi}_j^k(t_0) - \vec{\varphi}_j(t_0)) \]
Forming Differences

\[ L_{i}^{k} = \left| (\vec{x}_{k} + \Delta \vec{\chi}_{k}) - (\vec{x}_{i} + \Delta \vec{\chi}_{i}) \right| + T_{i}^{k} - I_{i}^{k} + c \cdot (\delta_{i} - \alpha_{i}) - c \cdot (\delta_{i}^{k} - \alpha_{i}^{k}) \]
\[ + \lambda^{k} \cdot N_{i}^{k} + \lambda^{k} \cdot (\varphi_{k}(t_{0}) - \varphi_{i}(t_{0})) \]

\[ L_{j}^{k} = \left| (\vec{x}_{k} + \Delta \vec{\chi}_{k}) - (\vec{x}_{j} + \Delta \vec{\chi}_{j}) \right| + T_{j}^{k} - I_{j}^{k} + c \cdot (\delta_{j} - \alpha_{j}) - c \cdot (\delta_{j}^{k} - \alpha_{j}^{k}) \]
\[ + \lambda^{k} \cdot N_{j}^{k} + \lambda^{k} \cdot (\varphi_{k}(t_{0}) - \varphi_{j}(t_{0})) \]

Forming single differences between two stations we obtain:

\[ \Delta L_{ij}^{k} = L_{i}^{k} - L_{j}^{k} \]
\[ = \left| (\vec{x}_{k} + \Delta \vec{\chi}_{k}) - (\vec{x}_{i} + \Delta \vec{\chi}_{i}) \right| - \left| (\vec{x}_{k}^{k} + \Delta \vec{\chi}_{k}) - (\vec{x}_{j} + \Delta \vec{\chi}_{j}) \right| \]
\[ + T_{i}^{k} - T_{j}^{k} - (I_{i}^{k} - I_{j}^{k}) - c \cdot (\delta_{i} - \delta_{j} - \alpha_{i} + \alpha_{j}) \]
\[ + \lambda^{k} \cdot (N_{i}^{k} - N_{j}^{k}) - \lambda^{k} \cdot (\varphi_{i}(t_{0}) - \varphi_{j}(t_{0})) \]
Forming Differences

\[ \Delta L^k_{ij} = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| - \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_j + \Delta \vec{\chi}_j) \right| \]

\[ + T^k_i - T^k_j - (I^k_i - I^k_j) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \]

\[ + \lambda^k \cdot (N^k_i - N^k_j) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]

\[ \Delta L^l_{ij} = \left| (\vec{x}^l + \Delta \vec{\chi}^l) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| - \left| (\vec{x}^l + \Delta \vec{\chi}^l) - (\vec{x}_j + \Delta \vec{\chi}_j) \right| \]

\[ + T^l_i - T^l_j - (I^l_i - I^l_j) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \]

\[ + \lambda^l \cdot (N^l_i - N^l_j) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]
Forming Differences

\[ \Delta L_{ij}^k = \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| - \left| (\vec{x}^k + \Delta \vec{\chi}^k) - (\vec{x}_j + \Delta \vec{\chi}_j) \right| \\
+ T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \\
+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \\
\]

\[ \Delta L_{ij}^l = \left| (\vec{x}^l + \Delta \vec{\chi}^l) - (\vec{x}_i + \Delta \vec{\chi}_i) \right| - \left| (\vec{x}^l + \Delta \vec{\chi}^l) - (\vec{x}_j + \Delta \vec{\chi}_j) \right| \\
+ T_i^l - T_j^l - (I_i^l - I_j^l) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \\
+ \lambda^l \cdot (N_i^l - N_j^l) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]
Forming Differences

\[ \Delta L_{i,j}^k = \left| (\vec{x}^k + \Delta \vec{X}^k) - (\vec{x}_i + \Delta \vec{X}_i) \right| - \left| (\vec{x}^k + \Delta \vec{X}^k) - (\vec{x}_j + \Delta \vec{X}_j) \right| \]
\[ + T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \]
\[ + \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]

\[ \Delta L_{i,j}^l = \left| (\vec{x}^l + \Delta \vec{X}^l) - (\vec{x}_i + \Delta \vec{X}_i) \right| - \left| (\vec{x}^l + \Delta \vec{X}^l) - (\vec{x}_j + \Delta \vec{X}_j) \right| \]
\[ + T_i^l - T_j^l - (I_i^l - I_j^l) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \]
\[ + \lambda^l \cdot (N_i^l - N_j^l) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]

Double differences between two satellites and receivers result in:

\[ \nabla \Delta L_{i,j}^{kl} = L_{i,j}^k - L_{i,j}^l \]

\[ = \left| (\vec{x}^k + \Delta \vec{X}^k) - (\vec{x}_i + \Delta \vec{X}_i) \right| - \left| (\vec{x}^k + \Delta \vec{X}^k) - (\vec{x}_j + \Delta \vec{X}_j) \right| \]
\[ - \left| (\vec{x}^l + \Delta \vec{X}^l) - (\vec{x}_i + \Delta \vec{X}_i) \right| + \left| (\vec{x}^l + \Delta \vec{X}^l) - (\vec{x}_j + \Delta \vec{X}_j) \right| \]
\[ + T_i^k - T_j^k - T_i^l + T_j^l - (I_i^k - I_j^k - I_i^l + I_j^l) \]
\[ + \lambda^k \cdot (N_i^k - N_j^k) - \lambda^l \cdot (N_i^l - N_j^l) - (\lambda^k - \lambda^l) \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]
Forming Differences

\[ \Delta L_{ij}^k = |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_i + \Delta \bar{x}_i)| - |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_j + \Delta \bar{x}_j)| + T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) + \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]

\[ \Delta L_{ij}^l = |(\bar{x}^l + \Delta \bar{x}^l) - (\bar{x}_i + \Delta \bar{x}_i)| - |(\bar{x}^l + \Delta \bar{x}^l) - (\bar{x}_j + \Delta \bar{x}_j)| + T_i^l - T_j^l - (I_i^l - I_j^l) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) + \lambda^l \cdot (N_i^l - N_j^l) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0)) \]

Double differences between two satellites and receivers result in:

\[ \nabla \Delta L_{ij}^{kl} = L_{ij}^k - L_{ij}^l = |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_i + \Delta \bar{x}_i)| - |(\bar{x}^k + \Delta \bar{x}^k) - (\bar{x}_j + \Delta \bar{x}_j)| - |(\bar{x}^l + \Delta \bar{x}^l) - (\bar{x}_i + \Delta \bar{x}_i)| + |(\bar{x}^l + \Delta \bar{x}^l) - (\bar{x}_j + \Delta \bar{x}_j)| + T_i^k - T_j^k - T_i^l + T_j^l - (I_i^k - I_j^k - I_i^l + I_j^l) + \lambda \cdot (N_i^k - N_j^k - N_i^l + N_j^l) \]
GNSS Phase Biases

- The ambiguity resolution in the zero difference processing does also only use double differences to get access to the integer ambiguities.
GNSS Phase Biases

- The ambiguity resolution in the zero difference processing does also only use double differences to get access to the integer ambiguities.

- The procedure requires that there is no satellite-specific component in the phase-related hardware delay $a_i$ and $a_j$ and/or that the satellite hardware delays $a_k$ and $a_l$ are identical for both stations.
GNSS Phase Biases

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  - the two satellites belong to different GNSS (even if they are using the same frequency: L1 and L5 for GPS and Galileo) because of a potential Inter-system bias (ISB)
GNSS Phase Biases

• The ambiguity resolution in the zero difference processing does also only use double differences to get access to the integer ambiguities.

• The procedure requires that there is no satellite-specific component in the phase-related hardware delay $a_i$ and $a_j$ and/or that the satellite hardware delays $a^k$ and $a^l$ are identical for both stations. Doubts in the consistency are recommended if
  • the two satellites belong to different GNSS (even if they are using the same frequency: L1 and L5 for GPS and Galileo) because of a potential Inter-system bias (ISB)
  • the signals are received on different frequencies because different hardware delays are expected (Inter-frequency bias, IFB) (alternatively, the IFB may be calibrated and corrected, e.g., for GLONASS ambiguity resolution).
Compatibility of Phase-Related Hardware Delay

- GPS Sat. $k$
  - GPS rec. $i$
    - $k$: L1W/L2W
    - $l$: L1W/L2W
  - GPS rec. $j$
    - $k$: L1W/L2W
    - $l$: L1W/L2W

- GPS Sat. $l$

---

Astronomical Institute, University of Bern
Compatibility of Phase-Related Hardware Delay

- GPS Sat. \( k \)
- GPS Sat. \( l \)
- GPS rec. \( i \) with \( k: \alpha_i(L1W) \) and \( l: \alpha_i(L1W) \)
- GPS rec. \( j \) with \( k: \alpha_j(L1W) \) and \( l: \alpha_j(L1W) \)

\[ k: \alpha_i(L1W) \quad \alpha_i(L2W) \quad \alpha_j(L1W) \quad \alpha_j(L2W) \]
Compatibility of Phase-Related Hardware Delay

```
    GPS Sat.  k
       /    \
      /      \
     /        \
GPS rec.  i
  k: L1W/L2W  l: L1W/L2W

    GPS Sat.  l
       /    \
      /      \
     /        \
GPS rec.  j
  k: L1W/L2W  l: L1W/L2W
```

\[ \begin{align*}
  k: \alpha_i(L1W) & \quad \alpha_i(L2W) \\
  l: \alpha_i(L1W) & \quad \alpha_i(L2W) \\
  k: \alpha_j(L1W) & \quad \alpha_j(L2W) \\
  l: \alpha_j(L1W) & \quad \alpha_j(L2W)
\end{align*} \]

ambiguity resolution possible
Compatibility of Phase-Related Hardware Delay

GPS Sat. $k$

GPS Sat. $l$

GPS rec. $i$
$k$: L1W/L2W
$l$: L1W/L2W

GPS rec. $j$
$k$: L1W/L2W
$l$: L1W/L2C

$k$: $\alpha_i(L1W)$
$l$: $\alpha_i(L1W)$

$k$: $\alpha_i(L2W)$
$l$: $\alpha_i(L2W)$

$k$: $\alpha_j(L1W)$
$l$: $\alpha_j(L1W)$

$k$: $\alpha_j(L2W)$
$l$: $\alpha_j(L2C)$
Compatibility of Phase-Related Hardware Delay

GPS Sat. \( k \)  

GPS Sat. \( l \)

GPS rec. \( i \)  

\( k: \alpha_i(L1W) \)  
\( l: \alpha_i(L1W) \)

\( k: \alpha_i(L2W) \)  
\( l: \alpha_i(L2W) \)

GPS rec. \( j \)  

\( k: \alpha_j(L1W) \)  
\( l: \alpha_j(L1W) \)

\( k: \alpha_j(L2W) \)  
\( l: \alpha_j(L2C) \)

"quarter cycle problem" – no resolution
Compatibility of Phase-Related Hardware Delay

GPS Sat. $k$

GPS Sat. $l$

GPS rec. $i$

$k$: L1W/L2W

$l$: L1W/L2C

GPS rec. $j$

$k$: L1W/L2W

$l$: L1W/L2C

$k$: $\alpha_i(L1W)$

$l$: $\alpha_i(L1W)$

$k$: $\alpha_i(L2W)$

$l$: $\alpha_i(L2C)$

$k$: $\alpha_j(L1W)$

$l$: $\alpha_j(L1W)$

$k$: $\alpha_j(L2C)$

ambiguity resolution possible
Compatibility of Phase-Related Hardware Delay

\[ k: \alpha_i(L1W) \quad \alpha_i(L2W) \quad k: \alpha_j(L1W) \quad \alpha_j(L2W) \]

\[ l: \alpha_i(L1W) \quad \alpha_i(L2W) \quad l: \alpha_j(L1W) \quad \alpha_j(L5Q) \]
Compatibility of Phase-Related Hardware Delay

Incompatible – no resolution

Graphical representation:
- GPS Sat. $k$
- GPS Sat. $l$
- GPS rec. $i$
  - $k$: L1W/L2W
  - $l$: L1W/L2W
- GPS rec. $j$
  - $k$: L1W/L2W
  - $l$: L1W/L5Q

Mathematical expressions:
- $k$: $\alpha_i(L1W)$, $\alpha_i(L2W)$
- $l$: $\alpha_i(L1W)$, $\alpha_i(L2W)$
- $k$: $\alpha_j(L1W)$, $\alpha_j(L2W)$
- $l$: $\alpha_j(L1W)$, $\alpha_j(L5Q)$
Compatibility of Phase-Related Hardware Delay

\[ k: \alpha_i(L1W) \quad \alpha_i(L2W) \]
\[ l: \alpha_i(L1W) \quad \alpha_i(L5Q) \]
\[ k: \alpha_j(L1W) \quad \alpha_j(L2W) \]
\[ l: \alpha_j(L1W) \quad \alpha_j(L5Q) \]
Compatibility of Phase-Related Hardware Delay

\[ k: \alpha_i(L1W) \quad \alpha_i(L2W) \quad k: \alpha_j(L1W) \quad \alpha_j(L2W) \]
\[ l: \alpha_i(L1W) \quad \alpha_i(L5Q) \quad l: \alpha_j(L1W) \quad \alpha_j(L5Q) \]

Be careful: \( \alpha_i(L5Q) - \alpha_i(L2W) \neq \alpha_j(L5Q) - \alpha_j(L2W) \)
Compatibility of Phase-Related Hardware Delay

$$\begin{align*}
\text{GPS Sat. } k &: L1W/L2W \\
\text{GPS Sat. } l &: L1W/L5Q \\
\text{GPS rec. } i &: k: \alpha_i(L1W) \quad \alpha_i(L2W) \\
&: l: \alpha_i(L1W) \quad \alpha_i(L2W) \\
\text{GPS rec. } j &: k: \alpha_j(L1W) \quad \alpha_j(L5Q) \\
&: l: \alpha_j(L1W) \quad \alpha_j(L5Q)
\end{align*}$$
Compatibility of Phase-Related Hardware Delay

Be careful: $\alpha^k(L5Q) - \alpha^k(L2W) \neq \alpha^l(L5Q) - \alpha^l(L2W)$
Compatibility of Phase-Related Hardware Delay

GPS Sat. \( k \)

GPS rec. \( i \)

- \( k: \) L1W/L5Q
- \( l: \) L1W/L5Q

GPS Sat. \( l \)

GPS rec. \( j \)

- \( k: \) L1W/L5Q
- \( l: \) L1W/L5Q

\[ k: \alpha_i(L1W) \quad \alpha_i(L5Q) \]
\[ l: \alpha_i(L1W) \quad \alpha_i(L5Q) \]

\[ k: \alpha_j(L1W) \quad \alpha_j(L5Q) \]
\[ l: \alpha_j(L1W) \quad \alpha_j(L5Q) \]

ambiguity resolution possible
Compatibility of Phase-Related Hardware Delay

\begin{align*}
\alpha_i(L1C)^{GPS} & \quad \alpha_i(L5Q)^{GPS} \\
\alpha_i(L1C)^{GAL} & \quad \alpha_i(L5Q)^{GAL} \\
\alpha_j(L1C)^{GPS} & \quad \alpha_j(L5Q)^{GPS} \\
\alpha_j(L1C)^{GAL} & \quad \alpha_j(L5Q)^{GAL}
\end{align*}
Compatibility of Phase-Related Hardware Delay

Be careful: \( ISB_i(L1C, L5Q) \neq ISB_j(L1C, L5Q) \)
Dependency of the Terms

\[ P_i^k = |(\vec{x}_i^k + \Delta \vec{x}_i^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k) \]

\[ L_i^k = |(\vec{x}_k^k + \Delta \vec{x}_k^k) - (\vec{x}_i + \Delta \vec{x}_i)| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta \varphi_i^k \]

**Antenna**
- Code: \( \Delta \vec{x}_i \)
- Phase: \( \Delta \vec{x}_i \)

**Hardware**
- Code: \( \delta_i \)
- Phase: \( \delta^k \)

**GNSS:**
- Code
- Phase

**Frequency:**
- Code: \( a_i \)
- Phase: \( \alpha_i \)

**Signal type:**
- Code

**ISB:** Inter-System Bias
- **IFB:** Inter-Frequency Bias
- **DCB:** Differential Code Bias
A GNSS antenna should be individually calibrated for each GNSS to consider the system-dependency of the $\Delta \vec{\chi}_i$ term.
GPS–GLONASS Antenna Bias: Coordinates

- A GNSS antenna should be individually calibrated for each GNSS to consider the system-dependency of the $\Delta \vec{\chi}_i$ term.

- The coordinate **GLONASS-GPS translation bias** shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center offset.
• A GNSS antenna should be individually calibrated for each GNSS to consider the system-dependency of the $\Delta \vec{\chi}_i$ term.

• The coordinate GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center offset.

• A related bias parameter was implemented for a background test solution at the CODE analysis center in early 2011.
GPS–GLONASS Antenna Bias: Coordinates
GPS–GLONASS Antenna Bias: Coordinates

- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
GPS–GLONASS Antenna Bias: Coordinates

- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
- Vector between GPS– and GLONASS–coordinates
GPS–GLONASS Antenna Bias: Coordinates

- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
- Vector between GPS– and GLONASS–coordinates
- two independent networks with independent datum definition
GPS–GLONASS Antenna Bias: Coordinates

- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
- Vector between GPS– and GLONASS–coordinates
- Two independent networks with independent datum definition
- Zero–mean condition over all GPS–GLONASS–bias in $xyz$
Differences between weekly coordinate solutions for GPS/GLONASS stations with and without estimating GLONASS-GPS translation biases:

GPS–GLONASS–Bias for the coordinates using IGS05.atx–antenna phase center corrections from weekly solutions of the years 2009 and 2010.
Differences between weekly coordinate solutions for GPS/GLONASS stations with and without estimating GLONASS-GPS translation biases:

<table>
<thead>
<tr>
<th>Station</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASH700936D_M</td>
<td>NONE</td>
</tr>
<tr>
<td>LEIAR25</td>
<td>NONE</td>
</tr>
<tr>
<td>LEIAT504GG</td>
<td>LEIS</td>
</tr>
<tr>
<td>NOV702GG</td>
<td>NONE</td>
</tr>
<tr>
<td>TRM55971.00</td>
<td>TPSH</td>
</tr>
<tr>
<td>TRM57971.00</td>
<td>TPSH</td>
</tr>
<tr>
<td>TRM59800.00</td>
<td>TPSH</td>
</tr>
</tbody>
</table>

GPS–GLONASS–Bias for the coordinates using IGS08.atx–antenna phase center corrections from weekly solutions of the years 2009 and 2010.
The troposphere GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center variation.
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The troposphere GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center variation.

- Troposphere estimates from GPS-only
- Troposphere estimates from GLONASS-only
The troposphere GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center variation.

- Troposphere estimates from GPS-only
- Troposphere estimates from GLONASS-only
- Difference between GPS– and GLONASS–troposphere series
The troposphere GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center variation.

- Troposphere estimates from GPS-only
- Troposphere estimates from GLONASS-only
- Difference between GPS- and GLONASS-troposphere series
- No constraints on the GPS–GLONASS–bias are needed
GPS–GLONASS Antenna Bias: Troposphere

GLONASS-GPS troposphere ZPD biases (for up to 143 IGS GNSS stations)

Time (GPS week)

Troposphere ZPD bias (mm)

Model switch from IGS05 to IGS08
Inter-System Antenna Bias

- The demonstrated way is one option to compensate for deficiencies in the (receiver) antenna calibration.
Inter-System Antenna Bias

- The demonstrated way is one option to compensate for deficiencies in the (receiver) antenna calibration.

- The currently used IGS08.atx and IGS14.atx sets of corrections provide sufficient calibration for legacy GPS and GLONASS measurements.
Inter-System Antenna Bias

- The demonstrated way is one option to compensate for deficiencies in the (receiver) antenna calibration.

- The currently used IGS08.atx and IGS14.atx sets of corrections provide sufficient calibration for legacy GPS and GLONASS measurements.

- The missing receiver antenna calibration values are a significant problem in the current status of multi-GNSS processing.
• The demonstrated way is one option to compensate for deficiencies in the (receiver) antenna calibration.

• The currently used IGS08.atx and IGS14.atx sets of corrections provide sufficient calibration for legacy GPS and GLONASS measurements.

• The missing receiver antenna calibration values are a significant problem in the current status of multi-GNSS processing.

• With the proposed method the influence of the deficiency on the results may be limited given that a sufficient amount of data are available.
THANK YOU for your attention

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